

Neutrinos produced by ultrahigh-energy photons at high red shift

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Some of the proposed explanations for the origin of ultrahigh-energy cosmic rays invoke new sources of energetic photons (*e.g.*, topological defects, relic particles, *etc.*). At high red shift, when the cosmic microwave background has a higher temperature but the radio background is low, the ultrahigh-energy photons can generate neutrinos through pair-production of muons and pions. Slowly evolving sources produce a detectable diffuse background of 10^{17} eV neutrinos. Rapidly evolving sources of photons can be ruled out based on the existing upper limit on the neutrino flux.

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Discovery of cosmic rays [1] with energies beyond the Greisen-Zatsepin-Kuzmin (GZK) cutoff [2] presents an outstanding puzzle in astrophysics and cosmology [3]. Many proposed explanations invoke a new source, such as superheavy relic particles [4–6] or topological defects [7–10], that can generate photons at both low and high red shifts. In understanding the origin of the ultrahigh-energy cosmic rays (UHECR), it is crucial to distinguish such sources from more conventional astrophysical ones [11,12]. In this *letter* we show that a diffuse background of neutrinos with energies $\sim 10^{17}$ eV can be generated by ultrahigh-energy photons at high red shift.

Generation of ultrahigh-energy neutrinos has been studied [8–18] for various sources at small red shift, for which muon pair-production can be neglected. However, a substantial flux of neutrinos could be produced at earlier times, when the propagation of photons was different from that in the present universe because the intergalactic magnetic field was weaker, the density of radio background was lower, and the cosmic microwave background (CMB) density and temperature were higher.

At red shift z the cosmic microwave background radiation (CMBR) has temperature $T_{CMB}(z) = 2.7(1+z)$ K. Because of this, at high red shift photon-photon and electron-photon interactions can produce pairs of muons and charged pions, whose decays generate neutrinos. This is in sharp contrast with the $z \lesssim 1$ case, where the photons do not produce neutrinos as they lose energy mainly by scattering off the radio background through electron-positron pair production and subsequent electromagnetic cascade [19,3]. The ratio of the CMBR density to that of universal radio background (RB) increases at higher z , and the processes $\gamma\gamma_{CMB} \rightarrow \mu^+\mu^-$ and $e\gamma_{CMB} \rightarrow e\mu^+\mu^-$ can produce muons, which decay into neutrinos: $\mu \rightarrow e\nu_e\nu_\mu$. The threshold for these interactions is $\sqrt{s} > 2m_\mu = 0.21$ GeV, or

$$E_{\gamma,e} > E_{\text{th}}(z) = \frac{10^{20}\text{eV}}{1+z} \quad (1)$$

Our discussion applies to any source of photons active

at high red shift. The latter requirement excludes some astrophysical sources [11]. Topological defects [7,8,10] and decaying relic particles [4,5], however, could operate even at $z \gg 1$. These sources are expected to produce photons with energies as high as 10^{20} eV. We will describe a neutrino signature of this class of sources.

At $z < 1$ the main source of energy loss for photons is electromagnetic cascade that involves e^+e^- pair production (PP) on the radio background photons. The radio background is generated by normal and radio galaxies. Its present density [24] is higher than that of CMB photons in the same energy range. The radio background determines the mean interaction length for the e^+e^- pair production. At red shift z , however, the density of CMB photons is higher by a factor $(1+z)^3$, while the density of radio background is either constant or, more likely, lower. Some models of cosmological evolution of radio sources [25] predict a sharp drop in the density of radio background at red shift $z \gtrsim 2$. More recent observations [26] indicate that the decrease of radio background at $z > 2$ is slow. However, one expects the CMB to become a more important source of energy losses for photons at higher z because of the $(1+z)^3$ increase in the density of CMB photons. Let z_R be the value of red shift at which the scattering of high-energy photons off CMBR dominates over their scattering off RB. Based on the analyses of Refs. [25,26], we take $z_R \sim 5$. Another source of energy losses in the electromagnetic cascade is the synchrotron radiation by the electrons in the intergalactic magnetic field (IGMF). This is an important effect for red shift $z < z_M$, where $z_M \sim 5$ corresponds to the time when the synchrotron losses are not as significant as the interactions with the CMB radiation. We will use the value $z_{\text{min}} = \max(z_R, z_M) \approx 5$ in what follows. As discussed below, a higher value of z_{min} , even as high as 10, would not make a big difference in the flux of the signature neutrinos.

Let us now consider the propagation of UHE photons at $z > z_{\text{min}}$. In particular, we are interested in neutrino-

generating processes, that is, reactions that produce muons and pions. For photon energies above the threshold for muon pair production (1), the reactions $\gamma\gamma_{CMB} \rightarrow e^+e^-$, $\gamma\gamma_{CMB} \rightarrow e^+e^-e^+e^-$ and $\gamma\gamma_{CMB} \rightarrow \mu^+\mu^-$ are possible. For $\sqrt{s} > 2m_{\pi^\pm} = 0.28\text{GeV}$ the charged pion production may also occur. Among the processes listed above, the electron pair production (PP) has the highest cross section for photon energies $E_\gamma \lesssim 5 \times 10^{20}\text{eV}/(1+z)$. Since the energies of the two interacting photons are vastly different, either the electron or the positron from PP has energy close to that of the initial photon. At higher photon energies, double pair production (DPP) becomes more important [32]. Four electrons, each carrying about 1/4 of the initial photon energy, are produced in this reaction. Thus, after an initial $\gamma\gamma_{CMB}$ interaction one ends up with one or more UHE electrons.

These electrons continue to scatter off CMBR. At lower energies, inverse Compton scattering (ICS), $e\gamma_{CMB} \rightarrow e\gamma$, converts high-energy electrons into high-energy photons [3]. However, at energies above the muon threshold, higher order processes, such as triplet production (TPP) $e\gamma_{CMB} \rightarrow ee^+e^-$ and muon electron-pair production (MPP) $e\gamma_{CMB} \rightarrow e\mu^+\mu^-$, dominate. For center of mass energies $s \gg m_e^2$, the inelasticity η for TPP is very small: $\eta \simeq 1.768(s/m_e^2)^{-3/4} < 10^{-3}$ [33,34]. One of the electrons produced through TPP, carries almost all $(1-\eta)$ of the incoming electron's energy. It can interact once again with the CMBR. As a result, the leading electron can scatter many times before losing a considerable amount of energy. Hence, the energy attenuation length λ_{eff} is much greater than the TPP interaction length: $\lambda_{\text{TPP}} \simeq \eta\lambda_{\text{eff}}$.

To see if neutrinos are produced, one must compare this *energy attenuation* length with the *interaction length* for muon pair production in processes like $e\gamma_{CMB} \rightarrow e\mu^+\mu^-$. Above the pion threshold, pion production is yet another channel that drains the energy out of the electromagnetic cascade and into neutrinos. We note that even a single neutrino-producing channel is enough for UHE photons to produce neutrinos at high red shift. The fact that there are several such channels makes little difference.

Let us compare the TPP energy attenuation length λ_{eff} with the interaction length for muon pair production. The interaction length is given by $\lambda^{-1} \simeq \langle n_{CMB} \rangle v\sigma$, and thus the ratio is $R = \lambda_{\text{eff}}/\lambda_{\text{MPP}} \simeq \sigma_{\text{MPP}}/(\eta\sigma_{\text{TPP}})$. For $s \gg m_e^2$ the cross section for TPP is [33,34]

$$\sigma_{\text{TPP}} \simeq \frac{3\alpha}{8\pi} \sigma_T \left(\frac{28}{9} \ln \frac{s}{m_e^2} - \frac{218}{27} \right), \quad (2)$$

where σ_T is the Thompson cross section. The MPP cross section in the energy range just above the threshold $5m_\mu^2 < s < 20m_\mu^2$ is of the order of 0.1 – 1mb, and the ratio $R \sim 100$.

Since $\lambda_{\text{eff}} \gg \lambda_{\text{MPP}}$, in the absence of dense radio background and intergalactic magnetic fields, all elec-

trons with $E > E_{\text{th}}$ pair-produce muons before their energy is reduced by the cascade. For muon production close to the threshold, each muon carries on average 1/4 of the incoming electron's energy [34]. Muons decay before they can interact with the photon background. Each energetic muon produces two neutrinos and an electron. The electron produced alongside the muon pair gets half or more of the incoming electron's energy; it can interact again with the CMBR to produce muons. This process can repeat until the energy of the regenerated electron decreases below the threshold for muon pair production. Higher energy electrons with energies $E > 2 \times 10^{20}\text{eV}/(1+z)\text{eV}$ can also produce pions through the reaction $e\gamma_{CMB} \rightarrow e\pi\pi$. Charged pions decay into neutrinos, while neutral pions reproduce photons. As explained above, it makes little difference through which channel the neutrinos are produced – as long as there is at least one reaction with a shorter mean free path than the energy attenuation length.

One can parameterize the rate of photon production as $n_x = \dot{n}_{\gamma,0}(t/t_0)^{-m}$, with $m = 0$ for decaying relic particles, $m = 3$ for ordinary string and necklaces, and $m \geq 4$ for superconducting strings [7–9]. Let z_{max} be the red shift at which the universe becomes opaque to ultrahigh-energy neutrinos. Its value is determined by the neutrino interactions with the relic neutrino background. The absorption red shift for neutrinos with energy $\sim 10^{17}\text{eV}$ is $z_{\text{max}} \sim 3 \times 10^3$ [22]. All neutrinos coming from red shift $z_{\text{min}} < z < z_{\text{max}}$ contribute to the present flux. The neutrino flux is

$$n_\nu = \xi \int_{z_{\text{min}}}^{z_{\text{max}}} dt \dot{n}_\gamma(z) (1+z)^{-4} \\ = \xi \frac{3}{-2a} \dot{n}_{\gamma,0} t_0 [(1+z_{\text{min}})^a - (1+z_{\text{max}})^a], \quad (3)$$

where ξ is the number of neutrinos produced per UHE photon, and $a = (3m - 11)/2$. We take $\xi \approx 4$ because one photon produces one UHE electron, which generates a pair of muons, which decay into four neutrinos. This is probably an underestimate because the remaining electron may have enough energy for a second round of muon pair-production. Also, pion decays produce three neutrinos each.

For $m < 11/3$, $a < 0$, and, according to eq. (3), most of neutrinos come from red shift $z \sim z_{\text{min}} \approx 5$. All these neutrinos are produced by photons with energies $E_\gamma > E_{\text{min}} = 10^{20}\text{eV}/(1+z_{\text{min}}) \sim 2 \times 10^{19}\text{eV}$. If decaying TD's or relic particles are the origin of the UHECR today, one can use the observed UHECR flux to fix the overall normalization constant $\dot{n}_{\gamma,0}(E > E_{\text{min}})$. We will use the photon fluxes calculated in [9,16,17]. For various sources, $\dot{n}_{\gamma,0}(E > E_{\text{min}}) \sim L^{-1} \int_{E_{\text{min}}} dE J(E)$, where $J(E)$ the differential photon flux, and L the length scale from which the photons are collected. Because the photon flux is a sharply falling function of energy, $\dot{n}_{\gamma,0}$ is dominated by photons with energies $E \sim E_{\text{min}}$. Relic particles ($m =$

0) and monopolonia ($m = 3$) cluster in galaxies and have $L \sim L_{\text{gal}} \sim 100\text{kpc}$, the size of our galaxy. Their over-density in the galaxy is $\sim 2 \times 10^5$ [9]. Necklaces ($m = 3$) on the other hand are distributed uniformly throughout the universe; for them $L = L_\gamma \sim 5\text{Mpc}$, the photon absorption length at these energies.

Using the photon flux from Refs. [9,16,17] one obtains the neutrino flux:

$$\phi_\nu \sim \begin{cases} 10^{-21}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}, & \text{relic particles } (m = 0), \\ 10^{-18}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}, & \text{monopolonium } (m = 3), \\ 10^{-16}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}, & \text{necklaces } (m = 3). \end{cases} \quad (4)$$

Taking $z_{\min} = 10$ reduces the flux of signature neutrinos from $m = 3$ sources only by a factor 2.

The energy of these neutrinos at red shift z is $E_\nu(z) \sim E_\mu/3$. It is then further red shifted by a factor $(1+z)^{-1}$. Assuming a falling photon spectrum, we expect most of neutrinos to come from photons near the threshold, eq. (1). We estimate the energy of these neutrinos after the red shift $E_\nu \sim 10^{17}\text{eV}$.

If the source in question is a slowly decaying relic particle or some other source with $m = 0$, the neutrinos produced at high red shift are probably not detectable. Of course, if the relic particles [5] or topological defects [10] produce UHECR through Z -bursts [23], neutrinos from Z decays can be detected.

Can other sources produce a comparable flux of neutrinos at $10^{17} - 10^{18}\text{eV}$? The neutrino flux $\phi_\nu \sim 10^{-16}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ at $E_\nu \sim 10^{17}\text{eV}$ exceeds the background flux from the atmosphere and from pion photo-production on CMBR at this energy [13,14,28], as well as the fluxes predicted by a number of models [18]. TD can produce a large flux of primary neutrinos. However, the primary flux peaks at $E_\nu \sim 10^{20}\text{eV}$, while the secondary flux peaks at $E_\nu \sim 10^{17}\text{eV}$ and creates a distinctive “bump” in the spectrum. Models of active galactic nuclei (AGN) have predicted a similar flux of neutrinos at these energies [12]. The predictions of these models have been a subject of debate [29]. However, every one agrees that AGN cannot produce neutrinos with energies of 10^{20}eV [35]. So, an observation of 10^{17}eV neutrinos accompanied by a comparable flux of 10^{20}eV neutrinos would be a signature of a TD rather than an AGN.

There is yet another interesting possibility. TD with $m \geq 4$, *e.g.*, superconducting strings, cannot give a large enough flux of UHECR because of the EGRET bound on the flux of γ -photons [3]. However, this does not mean they did not exist in the early universe. Neutrinos with energy 10^{17}eV are probably the only observable signature of some rapidly evolving sources that could be active at high red shift but would have “burned out” by now.

To summarize, we have shown that sources of ultrahigh-energy photons that operate at red shift $z \gtrsim 5$ produce neutrinos with energy $E_\nu \sim 10^{17}\text{eV}$. The flux

depends on the evolution index m of the source. A distinctive characteristic of this type of neutrino background is a cutoff below 10^{17}eV due to the universal radio background at $z < z_{\min}$. Detection of these neutrinos can help understand the origin of ultrahigh-energy cosmic rays.

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